Proposal for Generic Detector R&D for an Electron Ion Collider

A novel TPC readout system based on readout chips for Si-pixel detectors

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We propose to develop a novel readout system which is based on broadly available readout chips for Silicon pixel detectors. These chips (for instance the Timepix chip) offer the functionality of a TDC readout per channel in a highly integrated package. Our experience is coupled to the Timepix ASIC, which features 256 $\times$ 256 pixels with a pixel pitch of 55 μm $\times$ 55 μm. Each pixel can record either the time of arrival or the charge collected (time over threshold mode). We propose to combine the Timepix chip with a traditional pad plane, to allow for larger pads and thus coverage of a larger area.

1 Introduction

In the scope of the EIC physics program, semi-inclusive deep inelastic scattering (SIDIS) reactions in e-p, respectively e-A collisions play an important role regarding the spin of the proton, Fragmentation Functions (FF), Transverse Momentum Distributions (TMDs) by means of flavor tagging through hadron type, measuring Kaon asymmetries and cross sections, measuring

strangeness Probability Distribution Functions (PDFs), amongst others. This, in turn requires $p^{\pm}$, $K^{\pm}$, $p^{\pm}$ separation over a wide range in pseudorapidity, $|\eta| < 3$. It needs to cover the entire kinematic region in p_t and z, needs excellent particle identification (PID) and excellent momentum resolution at forward rapidities. TMDs need full azimuthal coverage around the virtual photon and a wide p_t coverage.
For identifying hadrons the technique via energy loss in the detection medium - dE/dx - with the combination of Ring Imaging Cherenkov (RICH) Counters can be used. They have to cope with a π/K ratio of 3 - 4, and a K/p ratio of ~ 1.
Figure 1 shows that in mid-rapidities a significant fraction of produced pions has momenta from lowest to about 1 - 3 GeV/c. The principal idea of a Time Projection Chamber (TPC) is

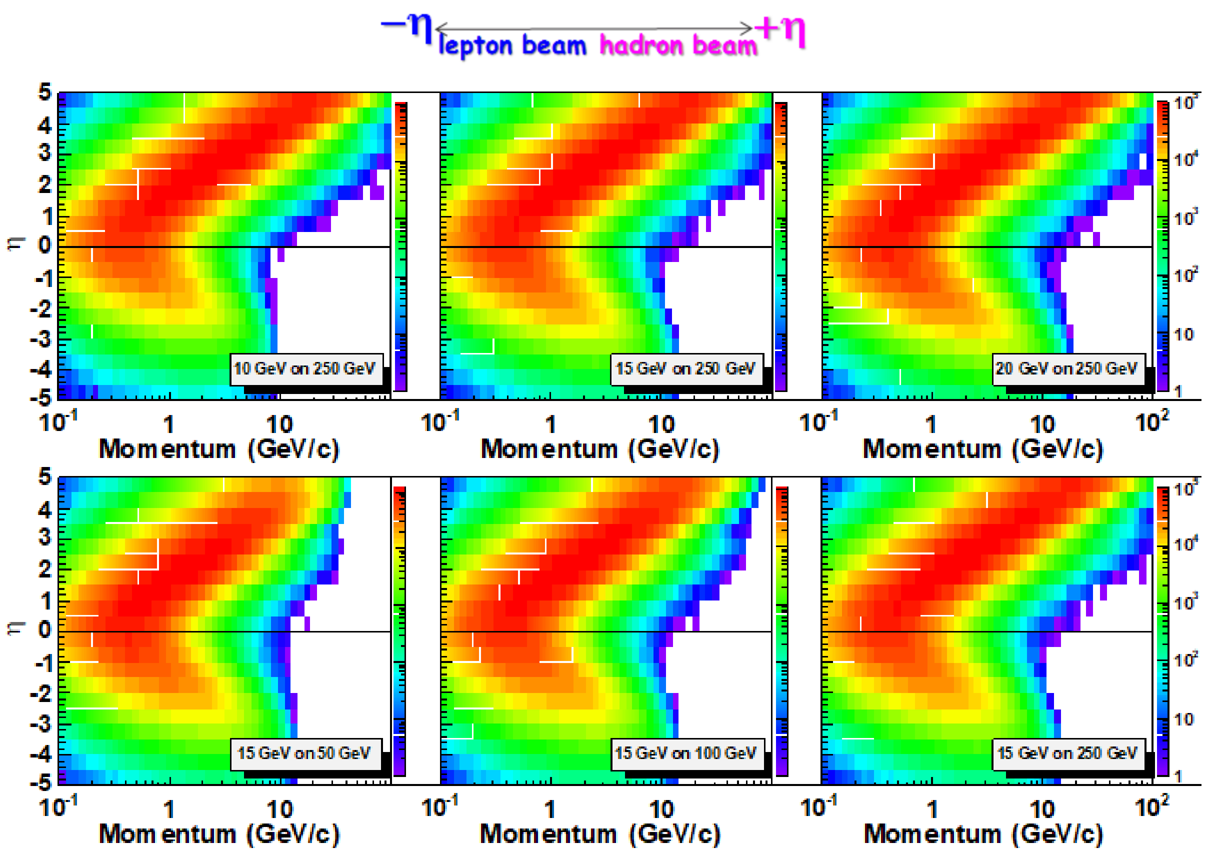

Figure 1: Pion kinematics in SIDIS. Upper: collisions with increasing lepton-beam energy and fixed hadron-beam energy, where hadrons are more and more boosted toward negative pseudorapidities. Lower: collisions with increasing hadron-beam energy and fixed lepton-beam energy, where hadrons' momentum at fixed pseudorapidities increases. It shall be noted that other hadron species beside $\pi^{\pm}$, like $K^{\pm}$ and $p^{\pm}$ show the same kinematics.

the combination of tracking and PID in a single detector. Gas ionization by a charged particle depends only on its velocity and the square of the charge but not on its mass. PID can, therefore, be achieved by simultaneously determining the particle momentum and its velocity from the ionization. When speaking of dE/dx; more precisely the localized ionization deposited near the track. This allows, in general, to distinguish between electrons/pions and amongst hadrons, at low momenta up to about 3-4 GeV/c, very well suited to perform PID tasks in mid-rapidities.

2 PID with a TPC

For particle separation, precise knowledge of two parts is required: the general dependence of dE/dx on the velocity and the ionization deposit along a specific track. The ionization loss drops as $1/\beta^2$ for low β $(= \frac{v}{c})$, goes through a minimum for $\beta\gamma$ = 3−4 $(\gamma = \frac{1}{\sqrt{1-\beta^2}})$, then rises logarithmically in $\beta\gamma$ (relativistic-rise region) until it reaches a plateau. PID is easy in the $1/\beta^2$ part but difficult in the relativistic-rise region. The dE/dx curve and in particular the slope of the relativistic-rise region and the plateau depend mainly on the gas and its pressure but also on the method used to measure the ionization. This function has to be determined from fitting the dE/dx measurements for well-identified particles in different $\beta\gamma$ regions, such as Bhabha electrons, cosmic muons and minimum ionizing pions.

The measurement of the energy loss of charged particles traversing the volume of a TPC is traditionally performed by counting the charge from the ionization deposited along the track. To measure the ionization loss of a particular track with reasonable precision, many samples have to be taken on the track. Ionization resolution is continuously improving with increasing number of samples for a given track length. So-called *straggling functions* (Figure 2) are providing typical energy loss distributions. They have long tails which are caused by so-called δ-electrons. Those have received a rather large amount of energy by the ionizing particle and allows them to further ionize atoms/molecules in the gas making them appear to be an ionizing particle by itself. These electrons lead to large fluctuations of the measured charge and further let the mean and the variance of the distribution become ill-defined. A more reasonable description is given by the most probable ionization I_{mp} and the FWHM. The procedure most widely used is the calculation of a truncated mean, denoted as *I*, as the mean of the lowest $p\%$ (typically p = 60 - 80) of the pulse heights. The cut reduces the effect of fluctuations due to the long tail. However, the cut also removes a fraction of track samples which in turn worsens the ionization resolution. Instead, it is of advantage to count the number of clusters the incident particle releases along its track. This is given by a Poissonian distribution with a significantly smaller width, resulting in a better correlation and particle identification power. To be more accurate, one has to consider particle separation power instead of ionization resolution. The separation of two particle species in dN/dx in units of the dN/dx resolution can be described by

$$\text{separation power} = \frac{\text{separation}}{\text{resolution}} \tag{1}$$

Figures 3-8 and the following examples are based on calculations for the LDC-TPC [3] read out with triple-GEM detectors, with Ar-CH_4-CO_2 (93-5-2) counting gas and 120 cm track lengths.

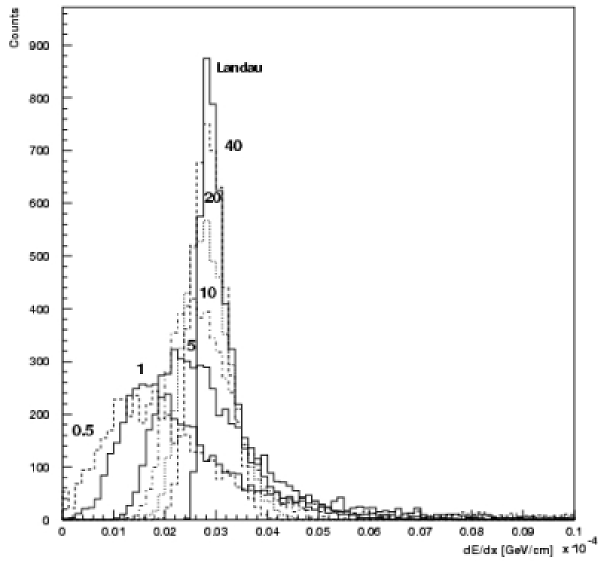

Figure 2: Energy loss distribution for a 3 GeV electron in Argon simulated with GEANT. The width of the layers is given in centimeters. The energy loss can readily be converted into a number of electrons. [1]

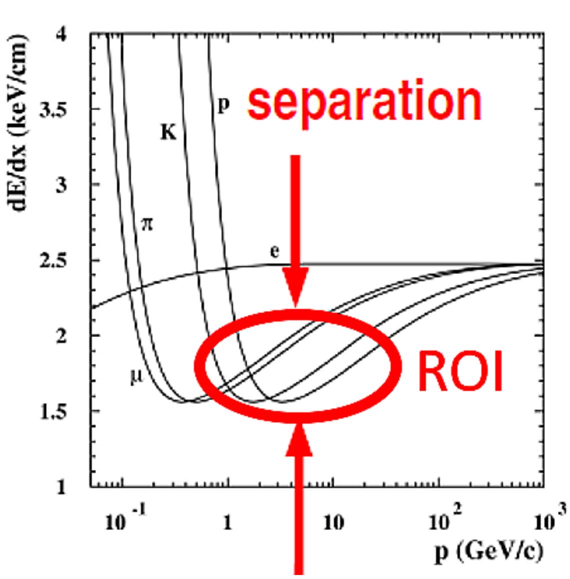

Figure 3: Energy loss from the modified Bethe-Bloch function [2]. The region of interest (ROI) can be enhanced if the proper separation in the ROI can be provided.

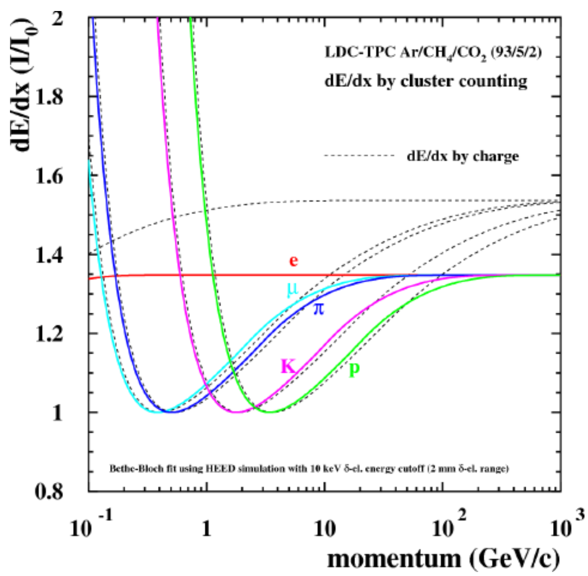

Figure 4: Comparison of energy loss from the modified Bethe-Bloch function, for charge measurement (dashed lines) and with cluster counting (solid lines).

Figure 3 shows that the momentum range for PID with a TPC can be quite enhanced if the separation can be achieved accordingly.
The Bethe-Bloch function differs when one is considering the two different techniques of obtaining dE/dx via charge counting and cluster counting (Figure 4). The difference stems from the fact that the charge measurement is highly sensitive to secondary electrons, which are more and more abundant at higher momenta due to δ-electrons. They are ignored if cluster counting is (perfectly) performed. The relativistic rise is truncated because the Fermi plateau is reached much earlier with cluster counting, but particle separation stops therefore at lower momenta. The shape as well as magnitude of particle separation power, however, differ significantly (Figures 5, 6). Cluster counting allows for a maximum separation at slightly larger momenta as compared to charge counting. It provides more separation below and less separation above certain momentum as compared to charge counting. The π/K separation power as shown in Figure 7 indicates that a 50% efficiency performs significantly better than the separation power obtained with charge counting. Even a 20% efficiency can compete with charge counting. In previous experiments with prototypes, a cluster counting efficiency of only 20-30% has been reached. However, as shown above, the resulting separation power is still better than by charge summation. Also, improved algorithms are expected to deliver a higher cluster counting efficiency. On the other hand, cluster counting can only work if a sufficient correlation between the position of the electrons of one cluster is preserved during drift. A perfect cluster counting efficiency of 100% is virtually impossible since the transverse diffusion of the electrons for effectively all gas mixtures will result in merging of clusters along the drift length of the electrons.

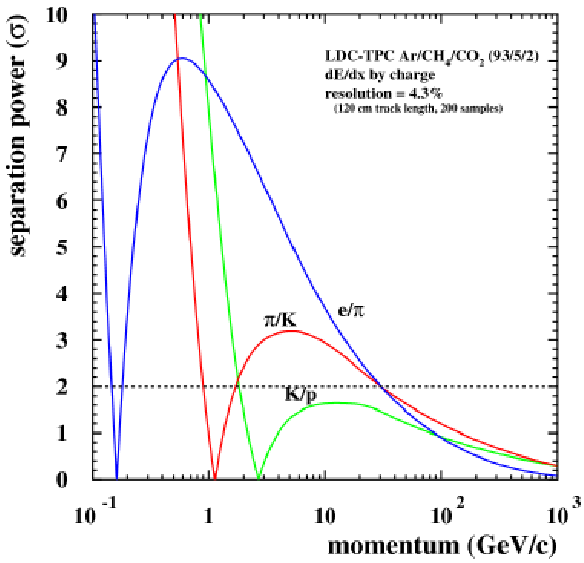

Figure 5: Separation power for charge counting, with energy resolution of 4.5% and track lengths of 120 cm and 200 samples along the track.

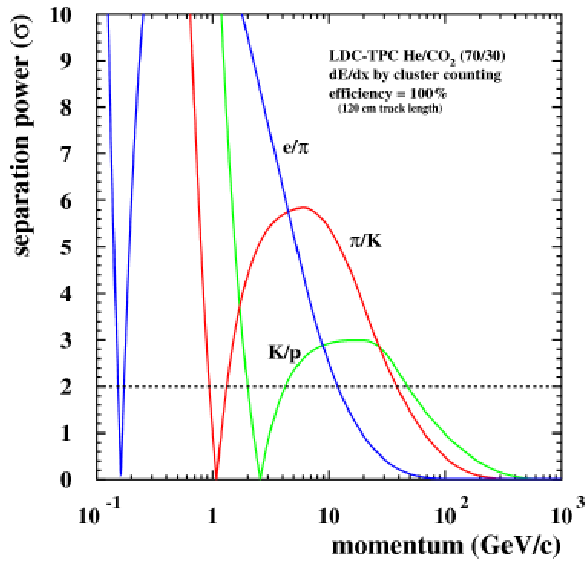

Figure 6: Separation power for cluster counting, for the same gas and track length as in Figure 5. A 100% counting efficiency is assumed.

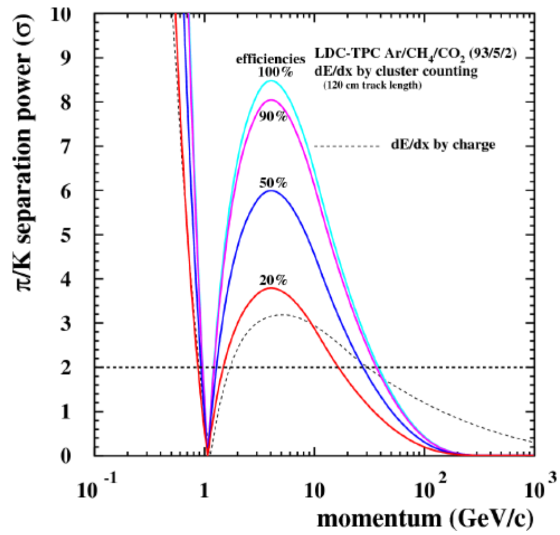

Figure 7: Separation power for π/K with cluster counting, based on different counting efficiencies (solid lines), compared to the separation power with charge counting.

Details needs to be investigated with simulations.

3 Description of a novel readout system

Modern gaseous detectors increasingly utilize micro-pattern gaseous detectors (MPGD). These systems, of which there are several derivatives, are characterized by amplification structures that are of a size similar to the intrinsic spatial resolution of $\mathcal{O}(100\ \mu\text{m})$ or smaller. These systems are read out either with pads, typically of a width of 1 mm or similar, or, as the extreme other case, with pixels of a size of 50 μm by 50 μm. In the traditional case a pad plane is prepared, through which the signals are routed to a readout system. To fully exploit the information of the pads the readout system quickly renders complex, and typically contains charge sensitive pre-amplifier and a fast analog to digital converter (FADC) to measure time and charge of the pulses. The pixel based readout on the other hand collects only minimal information per hit, usually time, based on a simple time to digital converter (TDC) circuit, whether a hit has occurred or not, and possibly charge. In the traditional case the challenge is to develop the electronics with a small enough footprint. In the pixel case, the challenge is to handle the large number of channels needed to instrument significant areas. Studies done over the past years have shown that a TDC based simplified readout can reach very similar resolutions as have been obtained with the FADC based approach.
To achieve the cluster counting capability, a sufficiently high granularity is needed for the TPC readout system. A comparison of two existing prototype systems is shown in Figure 9. The electron clusters are amplified by Gas Electron Multipliers (GEMs), creating charge clouds visible as blue blobs. The anode consists of 8 Timepix ASICs with their pixels as immediate

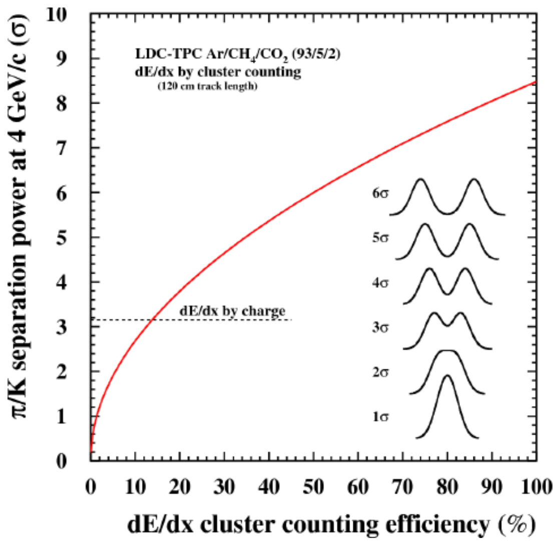

Figure 8: Separation power for π/K at p = 4 GeV/c, with cluster counting, improving with increasing counting efficiency. The right insert depicts a graphical representation of the various separation powers. The dashed line indicates the separation power with traditional charge counting.

sensitive anode, which has a pitch of 55×55 μm^2. The charge clouds are clearly identifiable – the granularity is even higher than needed, causing more data than necessarily required. On the other hand, the green overlay of a typical current pad-based readout system shows, that with its pads of about 1×6 mm^2 a cluster identification is not possible.
In addition to the cluster counting capability of such approach one has a significantly reduced amount of material in forward direction as the readout electronics is concentrated on a rather small area. For the Timepix chip 65,536 channels on an active area of about 2 cm^2. This is a very promising aspect for an EIC detector since one can significantly reduce material in the direction of forward scattered particles, across a TPC end plate. In particular in the direction of the scattered electron.

3.1 Proposed studies

We propose to develop a novel readout system which is based on the Timepix chip that offers the functionality of a TDC readout per channel in a highly integrated package. This proposal is based on an earlier work reported in [5]. The aim is to confirm expected results and to develop an advanced end plate (ceramic or silicon) based on the findings.
The Timepix ASIC features 256×256 = 65,536 pixels with a pixel pitch of 55 μm $\times$ 55 μm. Each pixel can record either the time of arrival or the charge collected (time over threshold mode). We propose to combine the Timepix chip with a traditional pad plane, to allow for larger pads and thus coverage of a larger area. Pad sizes will be around 300 μm to enable cluster counting, to give a large flexibility and to keep the channel number low at the same time.

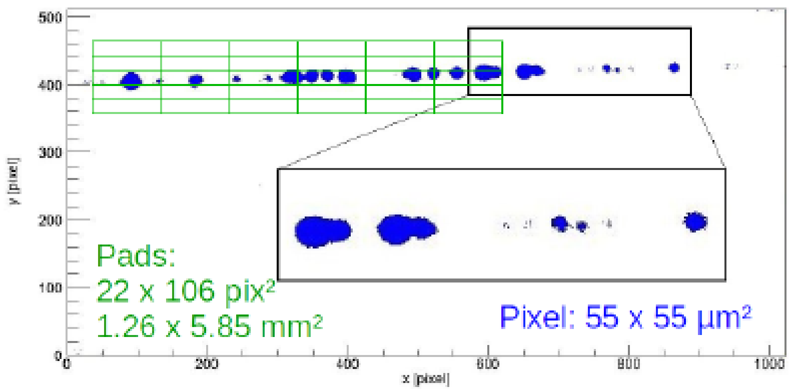

Figure 9: Event display of a track recorded with a Timepix Octoboard [4]. The activated pixels are shown in blue, the green overlay shows the pitch of a typical pad-based readout.

As depicted in Figure 10 GEMs will be used for amplification, small pads on a PCB form the anode and are read out by a Timepix ASIC. The connections from the pads are routed through the PCB to the ASIC which is bump bonded to the PCB surface, that needs to be sufficiently flat. Concerning technology, it is pioneering work to connect a pixel chip with such a small pitch directly to a PCB. The Timepix power and communication pads are on the same side of the ASIC as the pixels. They are usually connected by wire bonds. In the proposed approach these pads have to be connected by bump bonds to the PCB, which also hosts the further electronics elements including the connectors for the chip voltage supply and an I/O-cable plug. The data processing is conducted by a Scalable Readout System (SRS) developed by the RD51 collaboration at CERN. A Front-End Concentrator card (FEC) hosts a Field Programmable Gate Array (FPGA) that reads the data from the Timepix ASIC via an adapter card and a VHDCI-cable to the readout board. The FEC can be connected via Ethernet to a PC. Compared to traditional

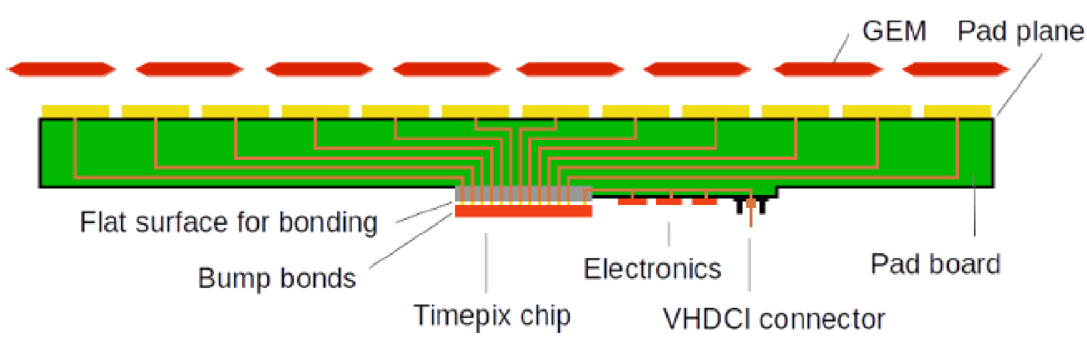

Figure 10: Structure of the proposed readout system.

pad-based systems our approach will have a higher granularity leading to charge cloud and possibly cluster identification capability beside improved double hit/track resolution and reduced occupancy. In addition, the Timepix ASIC allows for a significantly smaller footprint of the

readout electronics.
Traditional pixel-based systems, e.g., the InGrid system [6], have a higher granularity and record each electron with exactly one pixel. Pixel granularity combined with a GEM [7], does not increase the performance, but only the data output. Because the ASICs need some overhead area, and the module geometry, foreseen for cylindrical TPCs is not square like the ASICs, a pixel-based anode can currently cover only about 50% of the anode area in a setup with 12 *Octoboards* [8], or up to 63% with tightly stacked ASICs as suggested in [9].
Our approach measures each primary electron with several pads, allowing for position calculation using a fit. Furthermore, our approach allows to separate anode PCB and consequently for a coverage of more than 90% area, comparable to the traditional pad-based systems. Also, it is more flexible with regard to the granularity, since for a desired change in pad size it is required to only produce new PCBs and bond them to the ASICs, not to produce new ASICs with a different pitch.
The input capacitance of the pixels is a challenge for this project. Usually, pixel chips are bonded to sensors with the same pitch and small conductor volume and thus a small capacitance per sensor channel. Therefore, the Timepix ASIC is made for input capacitances below 100 fF, see Figure 11 [10]. In our approach, each connection goes through the board, and the capacitance is dominated by the line length with a value around 1 pF / inch. The pads and the bump bonds add only around 100 fF to the input capacitance. For line lengths between pad and pixel in the order of cm this clearly reduces the expected signal to noise ratio to a difficult level. This can probably be mitigated by an increased gas amplification in the GEM stack, leading to a signal of up to several 10k electrons. Overall, a solution to the capacitance challenge seems feasible and will be investigated with a test board.

Summary of challenges

- the Timepix chip is optimized for a low input capacitance (10-100 fF). Once connected to a pad plane a much higher capacitance will be present at the input (1-20 pF). We will need to establish whether the system will function in this configuration.
- The Timepix chip with its small pixels will need to be connected to the readout plane. This requires sophisticated and highly non-trivial interconnection technology. This must be done by bump bonding, which is regularly performed when connecting readout chips to silicon sensors. However, when connecting to a PCB, the usual and established technology is available only for significantly larger pitches.
- The routing on the PCB between the bump bond pads and the charge collection pads is non-trivial, and will need great care and advanced production techniques.

Summary of advantages

+ the footprint of the readout will be much reduced
+ the power consumption will be much reduced

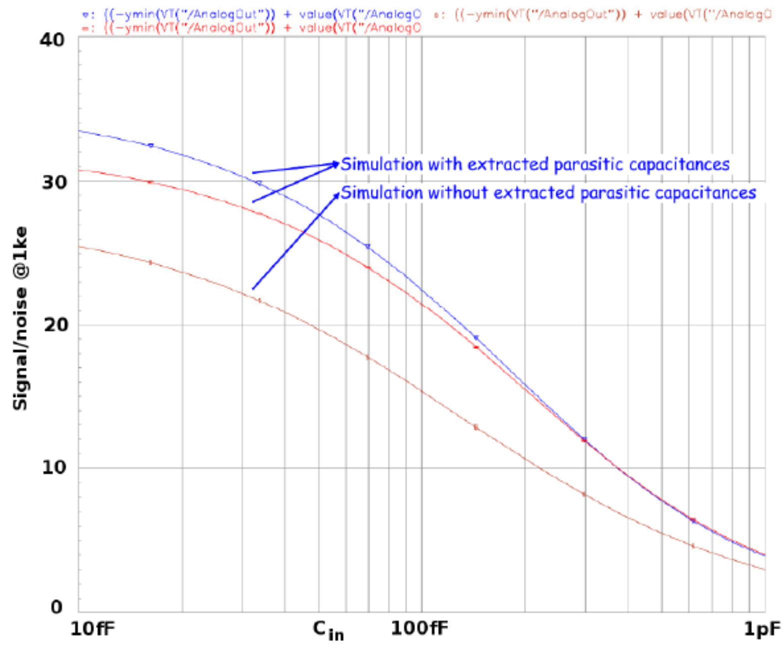

Figure 11: Simulated signal to noise ratio of the Timepix chip as a function of the attached input capacitance.

+ significant decreased material budget in forward direction
+ the system will be significantly cheaper than a traditional one
+ the system offers the possibility to reduce the size of the pads significantly, to profit from the increased precision, without having to go to the extreme case of pads of the size of the pixels on the chip.

3.2 R&DProgram

The R&D program is anticipated to be performed within two years.
A first test setup with a Timepix chip does exist at DESY which is based on a system that has been prepared in Bonn. A simple PCB has been produced and successfully bonded to the Timepix chip at the Karlsruhe Institute of Technology (KIT). As soon as this board will arrive at DESY it will be equipped for performing first tests. It is anticipated that first conclusions can be drawn regarding feasibility and performance shortly after. A simulation of the system is currently being developed at DESY that will answer questions concerning cluster counting and related problems.
In the first year a simulation study will be performed to establish the optimal size of the pads, for best resolution, with the largest possible pad size, adapted to the compact size of an EIC-TPC.
In a small setup routing technologies will be developed for very low charge signal by comparing

simulation results with some dedicated electrical tests, based on various approaches. From these studies also conventional readout pad planes could profit. Using standard PCB technology small prototype readout planes will be built and tested to establish the best procedure. For instance, the approach of focusing electrodes will be investigated, see Figure12. A test-of-

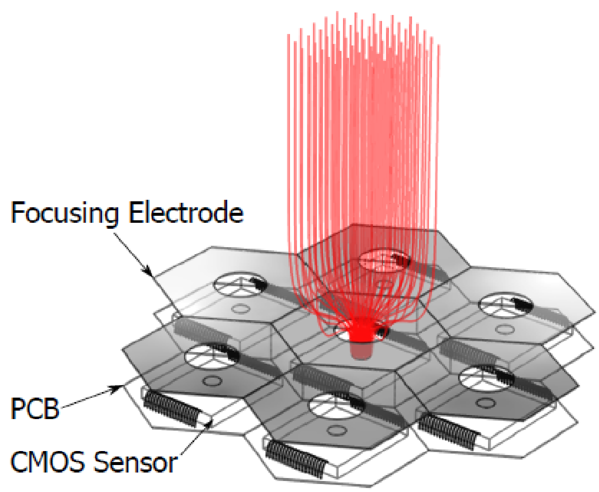

Figure 12: Focusing the charge signal onto ”fractional” pads, thus decreasing capacitance but maintaining the overall pad size.

principal experiment will be done where a few channels of the Timepix chip will be connected to the test pad-plane. This test will establish whether an acceptable signal to noise ratio can be reached, and whether the large mismatch in input capacitance mentioned above can be handled. The details of this setup will need to be developed, and in particular ways to connect the pixels on the chip will be tested. In this step also first connection techniques, like gold stud bumping or solder bump bonding will be tested. Bump bonding experience exists at one of the collaborating institutes, University of Bonn. Bonn has extensive experience in using the Timepix chip, and has pioneered the use of this chip in a TPC. DESY and SBU have extensive experience in developing traditional pad-based TPC/HBD/RICH with GEM readout systems.
In the second year, the main development will aim to work with a still limited but larger number of pixels of the chip. The pixels will be bonded to a prototype pad plane. Potentially a plane with a number of pads of $\mathcal{O}$(few 1000) could be considered, which would be enough to cover a significant area in an existing prototype TPC, and would allow a first realistic study of reachable precision in this readout configuration. For this step different technologies for the pad plane could also be investigated. A very promising option might be the use of low temperature co-fired ceramics (LTCC) for the readout. This would allow for a very flat pad plane (which is required to allow reliable bump bonding of the chip to the plane), excellent thermal properties to handle the heat of the chip and companies exist that offer an integrated pipe for cooling fluids such as two-phase CO_2. Also, the micro-via technology could be important to reach the high pad density on the PCB.
The main goal is the development of a pad-plane which can make use of the granularity of the

readout system. The material of the pad-plane is also a subject of investigation, e.g., the option to use ceramic, as mentioned above or silicon material for pad planes is under consideration and might also offer the possibility to integrate miniaturized cooling systems. Other pixel readout electronics than the Timepix chip will be investigated which might result in a less sophisticated readout plane. Chips like the FEI4 [11] or looking into the adaption of the Topmetal [12] chip will be investigated.

3.3 Budget request

All participating institutes will provide manpower with faculty, scientific staff, and graduate students. Bonn University and DESY have supporting funds which rendered possible the start of the studies as proposed here.
Faculty and staff will will not request funding for labor, however, we will request funding for two graduate students; one shared between Bonn University and DESY, and one at SBU, each for the anticipated duration of the project, i.e., two years.
We are requesting funding for bonding and connection tests of the boards to be produced as well as for the acquisition of Timepix chips and others within the first year. For the second year we will be requesting funding for the acquisition of larger boards, miscellaneous hardware, travel and participating in a test-beam, but is not listed in this document.

3.3.1 Baseline funding request

Our baseline funding request for year 1 is summarized in Table 1.

Year 1 cost item	DESY	University of Bonn	Stony Brook University	Sum
Salary graduate student	(1/2) $25k	(1/2) $25k	$48.5k	$98.5k
Board production	$10k	$20k	$10k	$40k
Timepix chip	-	-	$5k	$5k
Travel costs	-	-	$5k	$5k
Total request	$35k	$45k	$68.5k	$148.5k

Table 1: Budget request Year 1. One graduate student will be shared between DESY and Bonn University. Student requests are fully loaded.

3.3.2 Reduced funding request

Two reduced funding request scenarios are described.
Year 1: for a reduced budget scenario with nominal budget minus 20% the reduction would directly affect the items of board production and the acquisition of the Timepix chip. The students' salaries cannot be touched. Consequently, the board production has to be made cheaper by 50% and the acquisition of the Timepix chip has to be canceled. The cost reduction for

the boards would result in the acquisition of readout boards for only one of the participating institutes and would make the project unreasonable since the production of boards are based on various technologies to be tested. In he case nominal budget minus 40% the leftover will be salaries and the project would not be possible.

3.3.3 Deliverables

Establish the use of a Timepix based readout for gaseous chambers.
Establish connection technology to successfully bond the Timepix to a readout plane.
Study and establish alternative technologies (e.g. ceramics based) for pad planes for possible improved mechanical and thermal properties. If successful the proposed project could substantially contribute to the development of a new generation of highly granular and affordable gaseous detector systems.
Developing routing design for optimized signal transport for very low charge signals (10^3-10^5 electrons) confirmed by simulations and experiments.
For a year 2 continuation of the project it is expected to produce a nominal TPC module for an EIC detector with 5000 charge collection pads connected to 1-3 Timepix ASIC and verified in test beam.

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